The impact of urban environment on spatial navigation in elderly people with mild cognitive impairment

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Abstract

Spatial cognition deficits are particularly prevalent in early stages of Alzheimer's disease and in individuals with Mild Cognitive Impairment (MCI). Previous research using simplistic virtual reality (VR) settings was able to show such navigation impairments. However, the degree to which such results apply to more naturalistic environments remains unknown. Our study aims to test the hypothesis that spatial navigation in an elderly population with MCI could be improved by re-designing an urban space. Twenty-five MCI patients and a similar group of age- and gender-matched controls will be recruited to perform an urban spatial navigation VR task (uSNT). The uSNT is a modified version of the well-known virtual supermarket paradigm (designed to assess both egocentric and allocentric orientation processes), but the VR environment will be a real neighborhood of Lisbon. Specific interventions will be performed to various key parameters (street-level complexity, land-use, design, and green areas) and potential confounding elements (colors, textures, street occupation) of the urban scenario. Furthermore, eye tracking and electroencephalography data will be collected. Details of our task design and methodological approach to compare the navigation performance of both groups will be provided. In the future, we expect that the urban (re-)design interventions will positively impact on the navigation performance of MCI participants, being a clear proof-of-principle, that customize urban planning/design is key to enhance the autonomy and quality of life of such patients. Additionally, this research will establish the feasibility of replicating experimental conditions and ensuring consistency across different studies and subjects.

Introduction

Alzheimer's disease (AD) and other forms of dementia pose a significant and growing global health concern, being a leading cause of disability and mortality worldwide (GBD 2019 Dementia Forecasting Collaborators 2022). It has become clear that the pathophysiological onset of dementia may precede cognitive symptoms by several years, which has led to the characterization of mild cognitive impairment (MCI) as an intermediate state between normal aging and dementia (Cheng, Chen, and Chiu 2017; Petersen et al. 1999, 2018). MCI is marked by cognitive deficits in individuals, while their ability to perform instrumental activities of daily living (IADL) remains minimally impaired (Jongsiriyanyong and Limpawattana 2018). Despite a small percentage can remain in the pre dementia stages or even improve their cognitive function, there are no medications approved for MCI to prevent progression to dementia (Sachdev et al. 2013).

Navigation and spatial memory are prone to deterioration with normal aging (Tuena et al. 2021), a phenomenon also observed in the early stages of AD (Puthusseryppady et al. 2022). This is due to structural and functional changes in the neural network during aging, also related to the pathology of AD (as well as MCI), and is the major cause of spatial disorientation. This behavioral symptom leads patients to commit navigation errors in community spaces, potentially resulting in them becoming lost in both unfamiliar and familiar environments (Rowe et al. 2011).
From a neuroscience perspective, navigation depends on spatial memory, which involves processes such as encoding, storing, recognizing, and recalling spatial information about the environment, along with the objects and agents within it (O’Keefe and Nadel 1978). Moreover, spatial memory relies on two different reference representations that organize the information coming from the environment: 1) the egocentric representation, which pertains to the individual’s location in the environment and is grounded in subject-to-object relations; and 2) the allocentric representation, which pertains to object-to-object relations regardless of the individual’s location in the environment (Burgess 2008). Additionally, different neural circuits, governing separate spatial strategies, underlie egocentric and allocentric representations. The former is mediated by parietal lobe and dorsal striatum areas (Chersi and Burgess 2015), while the latter is processed by medial temporal lobe structures (such as the hippocampus and its associations with entorhinal cortex)(Ekstrom AD et al. 2003). In MCI (but also in AD), both egocentric and allocentric navigation strategies are impaired (Plácido et al. 2022; Puthusseryppady et al. 2020a).

Recent studies employing navigation tasks in novel environments (Da Costa et al. 2022; David Howett et al. 2019; Puthusseryppady et al. 2022) using virtual reality (VR) technology, have shown benefits for early diagnosis of AD and the identification of individuals at higher risk of dementia (Schoberl et al. 2020). Indeed, some authors propose that spatial navigation testing could serve as a sensitive diagnostic marker (Coughlan et al. 2018). Although this type of technology enables the implementation of navigation mechanisms similar to those activated in real-life navigation, current spatial navigation tasks lack in simulating real-world complexity, especially present in urban environments. Recognizing that not only the majority of people now reside in cities (United Nations 2018) but also that specific urban interventions may yield favorable outcomes for individuals with dementia (Marquardt, Bueter, and Motzek 2014), this aspect is particularly important. Indeed, there is a lack of understanding of how external factors (such as outdoor landmarks, road network structure, visibility, etc.) influence navigation in locations where patients feel disoriented (Puthusseryppady et al. 2020). This research could highlight potential environmental risk factors for spatial disorientation. Shinazi et al. (Schinazi et al. 2023) studied human navigation performance within a virtual city, however, their primary focus was not on assessing the influence of particular environmental features on spatial navigation.

The present work seeks to establish a novel framework that integrates insights from both neuroscience and urbanism fields to assess the spatial navigation abilities of people with MCI. This was accomplished through the application of non-immersive VR technology used to simulate and modify an actual neighborhood in Lisbon, Portugal. The future goal is to study the impact of different urban environmental features on spatial navigation. These adjustments could serve as a reference for policymakers in making decisions related to urban design.

**Reagents**

**Equipment**
2. Methods

2.1 Virtual reality system

The urban space was modeled in Blender 4.0 software using 1:1000 cartography as reference, made available by Lisbon City Council, and then imported to Unity Game Engine (version 2020 2.1). A virtual representation of Alfama and Graça neighborhoods, in Lisbon, Portugal, was generated and used as environment for the study of navigation (Figure 1. a-c).

2.2 Urban area characterization

One of the future goals is to advise policymakers, suggesting that specific environmental adjustments could offer valuable guidance for their decisions concerning urban design. Therefore, the urban area selected with this purpose in consideration.

The location sits within the historic city of Lisbon, situated between the Tagus River and São Jorge Castle. These neighbourhoods, once primarily residential, have now evolved into tourist destinations, characterized by their unique urban features (either their distinctive social occupations as well as their physical and functional layouts).

From a social perspective, the study area is occupied by an aging resident population, evidenced by a 62% increase in the elderly demographic over the past two decades (supported by the Census 2001, 2011, 2021 PORDATA Estatísticas sobre Portugal e Europa). However, it is also frequented by tourists, typically short-term visitors, and new residents – often young people and foreigners – with lifestyles differing significantly from the existing community. Consequently, it is considered multifunctional due to its diverse uses. In addition to its residential aspects (which are experiencing a gradual decline), the area boasts a collection of significant built heritage (such as churches, convents, streets, and squares that are emblematic of the network of public spaces), and shops and services aimed at catering to the constant flux or urban activity.

Regarding the urban morphology, Lisbon is known for its steeply sloping topography, giving rise to prominent elements like public staircases. While these staircases serve as notable landmarks, they also pose architectural obstacles for individuals with limited mobility. At the same time, the area is rich in viewpoints (formal and informal), offering panoramic vistas and serving as reference points with an open view system.
Urban layout

Concerning the urban layout and design, the area features a main street stretching 100 meters in length and 10 meters in width. This street serves as a vital connection between the upper and lower sections of Rua das Escolas Gerais (Figure 2. a-c), accommodating both pedestrian and vehicular traffic, including buses, private vehicles, and streetcars. The urban fabric is characterized by its irregularity, consisting of small built-up blocks surrounded by pedestrian or mixed streets of varying widths. Green spaces and trees are scarce within this environment.

The virtual model created based on this context aimed to preserve the unique attributes of the location, keeping the building volumes intact and accurately replicating the architectural features such as spans and colours. Additionally, efforts were made to retain the elements of the area such as streetcars, stairs, walls, and flooring type. These elements formed the foundation for establishing both control and optimized scenarios.

2.3 Spatial navigation task

The spatial navigation task was adapted from the recognized virtual supermarket test (VST), known for its ability to evaluate both egocentric and allocentric navigation strategies. We chose this test due to its previous use in highlighting navigation impairments in AD patients (Tu et al. 2015). In essence, the task involves presenting different videos of a shopping trolley moving around a virtual supermarket, from a first-person perspective. Each video features the shopping trolley starting from a fixed position and following a different route, whilst making a series of 90-degree turns, to reach a final destination within the supermarket. At the end of each video, participants are queried with sets of questions to test both egocentric and allocentric orientations. However, since our goal is to assess these spatial abilities within environments closely resembling real-world scenarios (namely, cities), and determine whether task performance improves through environmental manipulation, our virtual-reality space contained landmarks (Figure 3. a) and features intended to evaluate not only the construction of a mental map but also episodic memory, on the contrary of what happens in the VST. A detailed description of the VST can be found in a previous study (Tu et al. 2015). To reach this goal, we modeled one "control" scenario (see Table 1), which is identical to the current real-world conditions, and one "optimized" scenario, integrating dementia-inclusive planning and design guidelines (see Table 2). Moreover, we defined simple and more complex trajectories to have a mean of comparison and sensibility in task performance. Similar to the approach used in the VST, we developed a total of 16 videos (Figure 3. b), comprising 8 different trajectories replicated in both the control and optimized scenarios (first and second sessions, respectively). Among these, 4 were classified as simple, while the remaining were categorized as complex. Prior to the testing session, participants viewed a practice video trial (20 seconds, 2 turns) to introduce them to the urban environment and ensure that the task instructions were well understood. Additionally, there were two significant modifications: 1) after posing the first and second navigation questions (for each video), an extra question related to emotion (“how did you feel watching this video?”)
was included to explore potential correlations between spatial navigation and emotional states (Figure 3. c-e); and 2) following each testing session, participants were prompted with a series of scenario-specific questions, covering not only subjective evaluation of navigation ability but also aspects such as sense of belonging, fascination, and spatial coherence (see Table 3). The interval between the first and second testing sessions allowed participants to rest briefly and provide their responses. The task paradigm is presented in Figure 4.

**Complexity**

In the VST test, complexity is simply defined by adding a greater number of 90-degree turns (5 turns instead of 3) and time (40 seconds instead of 20), as the layout of the virtual environment was not built to contain distinct spatial representations or notable landmarks. Within an urban environment, even a short linear trajectory can become highly complex if it involves a variety of different and unpredictable elements, such as colors, textures, street activity, as well as factors like lighting conditions, weather, ambient noise, and traffic (Brunec et al. 2023; Marquardt, Büeter, and Motzek 2014b). The brain's mechanisms for processing such diverse information are inherently computationally complex. This led to the requirement for quantifying complex videos, considering urban characteristics. For this matter, variables such as the relativized entropy, connectivity, the isovist, field of view, and the buildings facades complexity were selected. Entropy indicates the degree of space accessibility – a higher entropy value suggests greater difficulty in reaching other areas within the space, and vice versa. Connectivity measures all direct connections that each axial line possesses to other axial lines within its nearby vicinity. Moreover, the isovist represents the area surrounding a point (or centroid) within which an object can freely move in any direction until it encounters an obstacle. In spatial analysis, this area is commonly referred to as a viewshed, and the extent of visibility or movement is measured by the maximum line of sight from the point where the isovist is defined. Figure 5 represents the visual integration of these metrics within the map of the city, and Table 4 shows their demography.

We have also computed the Field of View (FOV) analysis in a 3D environment, from to visualize and calculate the amount of space that can be seeing from any observer with a specific height from a certain given point in space (Figure 6). The process consists of defining a set of check points through the street, to be able to map and calculate the visual field for each checkpoint, and for selecting the facades that fall within that field of view that will afterward be considered for the complexity measurement.

Lastly, the building façade complexity was computed using the box-counting method (Wolfgang E. Lorenz and Matthias Kulcke 2021), which consists of four phases to calculate the fractal dimension of the façades (Francesco Leopardi 2023) within the visual field of the observer, e.g. 1) create a first pre-defined grid and count the boxes that contain parts of the geometry; 2) Overlaying a second grid, where the cell dimensions are half of those in the previous grid, and counting the boxes that contain parts of the configuration; 3) Additional grid systems with cell dimensions always equal to half of the cell in the previous grid, until the minimum box size contains the smallest detail of the object. Then count the
number of boxes for each grid that contain parts of the geometry; 4) create a double logarithmic graph, where the x-axis represents the values $\log(ri)$, where $ri$ can denote the scale factor between the initial grid and the subsequent ones, or the number of boxes arranged along the longer side of the object. Along the y-axis, the values $\log(Ni)$ are represented, where $Ni$ represents the number of filled cells for each grid. The slope of the regression line that approximates the points $[\log(ri);\log(Ni)]$ represents the fractal dimension $Db$, that measuring the complexity of the building façades.

**Urban scenarios**

One first scenario, designated as control, was created to reflect the current urban reality (Figure 7). The strengths and weaknesses of the space are documented in Table 1. Subsequently, an optimized scenario was devised, taking into account dementia-inclusive planning and design guidelines (Dementia-inclusive planning and design guidelines 2023). All modifications made are present in Table 2 and are aimed at improving 1) route’s visibility and specific visual information: the integration of reference points, and the establishment of specific zones with unique characteristics have been identified as helpful for residents’ wayfinding abilities; 2) sense of place: a multi-disciplinary area of research has defined sense of place (SOP) as a combination of beliefs, emotions, and behavioral commitments that result in a sense of specialness for a physical setting – McCunn (McCunn and Gifford 2021) reported that, in community settings, stronger SOP is associated with easier recall and navigation through mental maps, in urban environments; and 3) aesthetics: through the deletion of frequent sights of garbage, graffities, and disrepair.

**Task metrics**

Ultimately, the performance in the spatial navigation task was evaluated using five outcome measures. For the first navigation question (“Which way should you turn to face the point where you started?”), the reaction time, and the angular error were collected. Regarding the second question (“Touch the map of the environment to show where you finished”), reaction time was also considered along with absolute distance error on the map, defined as the Euclidean distance between estimated and actual starting point locations. Additionally, two secondary outcomes were included to deconstruct absolute distance errors into their proportional angular and linear components. These measures helped mitigate between-trial variability stemming from the pseudo-random generation of trajectories and starting points, which could influence task difficulty/complexity. A third type of outcome measure involves evaluating the variability in task performance across tasks and over time, both between and within participants. In healthy aging, it is believed that increased within-subject variability in spatial navigation tasks may indicate an increase in neural noise which, in turn, could stem from a disruption in executive control systems and/or dysfunction in neuromodulatory systems (Harris and Wolbers 2012). The intention was to evaluate these statistical outcome measures in patients with MCI. Qualitatively, assessments of spatial coherence, compatibility,
as well as perceptions of fascination, oppressiveness, and navigation ability were considered for each VR scenario (Table 3).

**Troubleshooting**

**Time Taken**

**Anticipated Results**

3. Discussion

The introduction of VR testing has prompted numerous studies to investigate spatial navigation within virtual environments. This is primarily due to the capability of VR environments to be completely controlled and replicated across participants (Bing Liu, Linfang Ding, and Liqiu Meng 2021). Fundamentally, these studies have proven valuable in highlighting how AD pathophysiology gives rise to impairments in cognitive processes involving spatial orientation and navigation, further emphasizing the possibility of such impairments becoming potential markers of the disease. While VR studies focus on the underlying neurocognitive factors of spatial disorientation, in relatively simple environments, there remains a gap in understanding how these factors link to external, urban components, found in the complex environment where these impairments occur. By modeling a VR environment that replicates the present condition of a particular neighborhood in Lisbon, Portugal, our aim was to establish a framework for studying the impact of environmental components (such as visibility and visual information, building complexity, sense of place, and aesthetics) on spatial navigation in a population with MCI. Through the development of the methodology, several aspects warrant discussion. Until recently, most of VR used in research was presented on a desktop display, with movement controlled by a joystick or keyboard (Coutrot et al. 2019). Nowadays, immersive VR, which utilizes headsets and virtual goggles, and in some instances allows for walking, has been employed for navigation testing. This offers the advantage of incorporating body-based cues crucial for navigation. However, these interfaces pose challenges for older people, who are less exposed to technology, and cybersickness remains a significant concern, as such experiences have been shown to induce discomfort in AD patients. Although both immersive and non-immersive VR have advantages and disadvantages, the mentioned negative aspects led us to opt for a non-immersive VR setting. Furthermore, the decision to use video presentations made the task considerably simpler, and thus more engaging and intuitive when compared to immersive setups, while also removing the impact of technology familiarity on task performance.

Moreover, additional potential cofounding variables were considered and collected, including age, sex, space familiarity, years of education, as well as surveys assessing stress, attention, sleep, memory, and spatial cognition. These were selected to account not only for cognitive abilities but also for the affective state of the participants, given the cross-sectional design of the experiment.
Regarding the environmental modifications between the control and the optimized scenarios, they were based on dementia-inclusive planning and design guidelines, and with an intention that, in the future, these adjustments could serve as a reference for policymakers in making decisions related to urban design. Even if it is just indirectly, the ultimate goal is to start reducing and mitigating inequalities in urban areas that impact vulnerable groups. Furthermore, this implies that these selections were made not only for their potential positive results but also for their practical applicability in real-life situations. The primary modifications were those that directly affected urban landmarks or reference points. In this context, a landmark represents one item that is stably related to specific locations or directions on the map, playing a crucial role in anchoring the cognitive map to the world. In other words, for a cognitive map to be useful, the organism must possess a mechanism for linking map coordinates to stable elements (landmarks) of the environment that can be identified by perceptual systems. These modifications can influence processes related to egocentric and allocentric navigation strategies, as they may impact the mental calculations of distances between the subject and a landmark as well as between landmarks. Secondary modifications were made to enhance the general perception of cleanliness and safety within the environment. These adjustments (such as “remove the garbage”, “introduce handrails”, “replace steps with escalators”, see Table y) were chosen to explore potential relationships between emotional states and spatial navigation performance. Emotional states were characterized not only by subjective evaluation but also through data collected from the brain (electroencephalography marker of arousal), electrodermal activity (EDA), and heart rate variability (HRV). Some studies suggest that the “affective charge” of spaces is important for wayfinding: environments with strong emotional associations are more memorable, negatively-laden landmarks are associated with improved wayfinding performance and recognition and positively-laden landmarks and high arousing landmarks are linked to enhanced route drawing abilities(Gregorians et al. 2022). Moreover, this might align with research indicating that the presence of safety range may serve as a protective factor against the recurrence of getting lost in AD patients (Kwok et al. 2010). Lastly, to assess potential differences between subjective perceptions of navigation abilities and more objective measures, analyses of EEG time-frequency and structural fMRI data, focusing on brain regions related to egocentric and allocentric navigation strategies, will be carried out. The results will be compared to the survey provided in Table Z (questions related with navigation), for both healthy subjects and patients.

4. Conclusion

The present work aimed at developing an innovative framework for evaluating how environmental factors - such as route visibility and visual information, the sense of place, and urban aesthetics - influence spatial navigation abilities in both healthy subjects and those with mild cognitive impairment. To reach the goal, a virtual reality environment was modeled to simulate real-world settings, and the development of two scenarios featuring distinct urban conditions enabled the testing of the hypothesis. By using neuroimaging techniques like electroencephalography, alongside technologies such as eye tracking and wristbands for monitoring electrodermal activity and heart rate variability, we can obtain robust
physiological data regarding the ongoing processes during each phase of the task. In the future, by showing that urban planning can potentially impact a cognitively impaired population, we intend to provide evidence that could be used to guide practice of urban design for other mental health conditions and ultimately start reducing inequalities in urban areas that affect vulnerable groups, such as those with cognitive disorders.

References


Francesco Leopardi. 2023. “City and Complexity: The Case of Rua Das Escolas Gerais in Lisbon Assessing the Influence, through the Analysis of Biosignals, of the Effects Generated by the Complexity of the Urban Environment within the Observers’s Field of View.” doi:10.13140/RG.2.2.16229.20969.


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**Figures**

![Figure 1](image-url)
Virtual reality environment of the studied area in the city of Lisbon.

Figure 2

Urban layout of the studied area in the city of Lisbon.

Figure 3

Spatial navigation task.
**Figure 4**

Task paradigm.

**Figure 5**

Virtual integration map of the city.
Figure 6

Field of view for the Rua das Escolas Gerais.

Figure 7

Virtual reality of the urban environment.

Supplementary Files

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- Tables.docx
• FigureLegend.docx